TUNING OF PID CONTROLLER FOR HIGHER ORDER SYSTEM

A Thesis Submitted in Partial Fulfilment

of the Requirements for the Award of the Degree of

Master of Technology

in

Electronics and Instrumentation Engineering

by

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National Institute of Technology, Rourkela

Odisha- 769008, India

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CERTIFICATE

This is to certify that the thesis report entitled **“TUNING OF PID CONTROLLER FOR HIGHER ORDER SYSTEM”** Submitted by **Mr. SANDEEP KUMAR** bearing roll no. **212EC3154** in partial fulfilment of the requirements for the award of Master of Technology in Electronics and Communication Engineering with specialization in **“Electronics and Instrumentation Engineering”** during session 2012-2014 at National Institute of Technology, Rourkela is an authentic work carried out by him under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University / Institute for the award of any Degree or Diploma.

Prof. Umesh Chandra Pati

Place:

Associate Professor

Date:

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Dedicated to My Family,
Teachers and Friends

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ABSTRACT

PID controllers have been widely used in process control industries because of its implementation and tuning advantages. It is mainly used because of its relatively simple structure and robust performance. It seems conceptually very easy to achieve multiple objectives such as short transients and high stability, but tedious in practice. The speed of the response of the system is inversely proportional to the time constant of the dominant pole of the plant. Thus, it is advisable to design such a plant which has pole very near to the origin.

Better responses can be found in different systems with different dynamics, like those with low order or higher order, monotonic or oscillatory responses and large dead time or small dead time. Tuning of PID controllers for FOPDT is very simple and common practice. Many methods have been found out which can generate the algorithm for FOPDT model, but FOPDT model is unable to generate peaks for monotonic processes.

This method is basically developed on a second-order modeling technique which is calculated by two methods. First part of the research work is based on the root locus method. In this method poles are allocated in such a way that model poles are cancelled out by controller zero. But, exact cancellation is not possible. Hence the controller cancels out the model pole which is nearest to its exact value. In this method, the higher order system is reduced into a second order system and then tuning of the PID controller is done by damping ratio and speed of the response.

Second part of the research work is based on the Bode plot method in which phase crossover frequency, gain crossover frequency and bandwidth frequency are used. These three frequencies continue the process further by using multiplication technique and the values of a, b, c and L can be found out, which form a SOPDT model. Tuning of PID controller is somewhat similar to the first method, in which controller zeros cancel out model poles. In this method, Routh-Hurwitz criterion is also used to find the value of k for which system would be critically stable. It is a necessary condition for determining finite phase crossover frequency.

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LIST OF ABBREVIATIONS

PID	Proportional-Integral-Derivative
FOPDT	First Order Plus Dead Time Model
SOPDT	Second Order Plus Dead Time Model
OS	Overshoot
ST	Settling Time
ZN method	Ziegler Nichol method
IMC	Internal Model Control
IAE	Internal Absolute Error
ITAE	Internal Time-Weighted Absolute Error
ISE	Internal Squared Error
GPM	Gain Phase Margin
CLS	Close Loop System
OLS	Open Loop System
BW	Bandwidth

CHAPTER 1

INTRODUCTION OF PID CONTROLLER

- Overview
- Basic Building Block of Closed Loop System
- Different Parameters of Closed Loop System
- Basic Building Block of PID controller
- PID controller Parameters
- Motivation
- Objectives
- Thesis Organisation

1 Introduction of PID Controller

PID Controller is extensively employed in process control industries. The PID controller tuning technique is adopted for determining the proportional, integral and derivative constants of the controllers which depend upon the dynamic response of the plants. PID controller is introduced into the closed loop system by cascading it to the forward path. According to the requirements, the controller is cascaded either into the forward path or in the feedback path.

1.1 Overview

The PID controller contains three different parameters and hence it is also called three term control system which can also be written as proportional, integral and derivative. These terms are defined as variables of time as P defined as present Difference (error), I defined as an integration of past differences (errors) and D is defined as prediction of future differences (errors). These three elements control all the processes in the process industries [1].

PID controller is the best controller in the absence of any information regarding the process. After tuning the PID controller, the controller can be used for different control action for any process requirement. The error can be defined by the process of the controller, but it does not the guarantee about the optimal control of the system.

Many applications might require two some specific control action to get the appropriate system and that can be found by setting the other parameters to zero. If suppose 100% accuracy is required, then the PI controller is sufficient to achieve the requirements. D parameter is responsible for the measurement noise so it is suitable to ignore it till any application requires using it. When the speed of the system is a priority, then the PD controller is suitable and then an integral parameter is set to zero. So PID controller is used as per requirement of different processes. PID controller takes input as a difference between set point and feedback signals.

1.2 Basic Building block of Closed Loop System

A control system that changes the output based on the error which is calculated as the difference between the set point and the feedback signal, is called as close loop system. The Fig. 1.1 shown below is the basic diagram of the CLS.

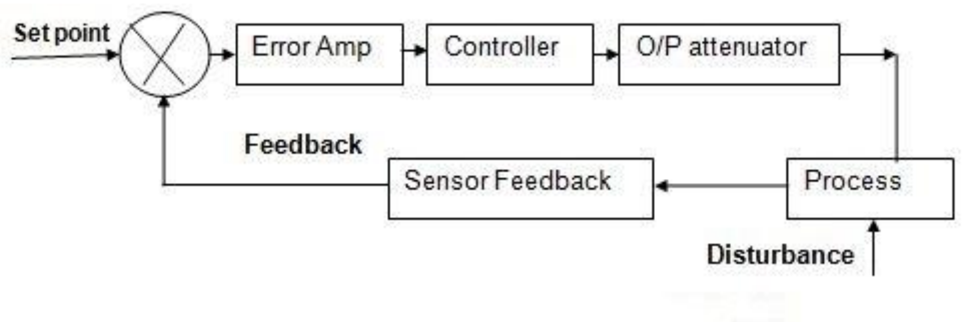

Fig. 1.1: Block diagram of close loop system

Reference input: Externally produced input that is independent of feedback control system and produce a signal.

Error Detector: It is a device which sums or compress the signal obtained from the feedback and the reference input.

Control Element: It produces the desired output from the actuating signal.

Disturbance: Unwanted signal that deviates the result of the system.

Feedback Signal: Element which help in providing the controlled output to be feedback to the error detector for comparison with the reference input signal.

Controller Output: It is the quantity that required to be controlled at the desired level.

Derive the transfer function of feedback system from Fig. 1.2 which is defined as the ratio of output signal to the input signal put all other incoming signals to zero.

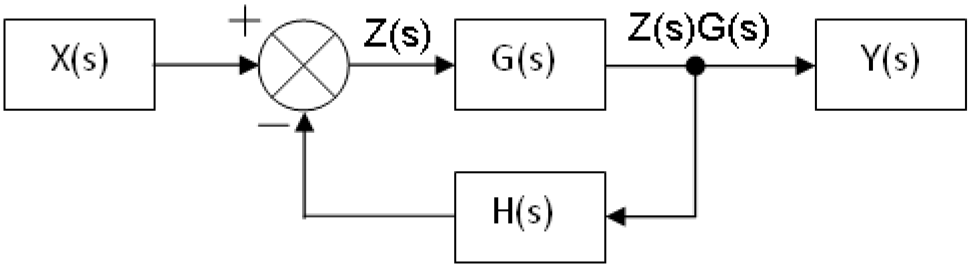

Fig.1.2: Close loop system

X (s): Input signal

Y (s): Output signal

Z (s): Actuating signal

H (s): Feedback path transfer system

G (s): Forward path transfer function

The T.F. of the system can be calculated as,

$$\frac{Y(s)}{X(s)} = \frac{G(s)}{1 + G(s)\mathrm{H}(s)} \tag{1.1}$$

The error can be calculated as,

$$\frac{\mathrm{E}(s)}{X(s)} = \frac{1}{1 + G(s)\mathrm{H}(s)} \tag{1.2}$$

1.3 Time Response specifications

The performance of a controlled system is determined as a transient response of a unit step input because it is easy to get the response by using step value as an input which is shown in Fig.1.3. There are two types of response of a CLS.

(1) Transient Response

The response of the system before equilibrium is called as the transient response of the system. It is not applied for on/off system.

(2) Steady State Response

When system attains equilibrium and no transient effect present, then that response is called as a steady state response.

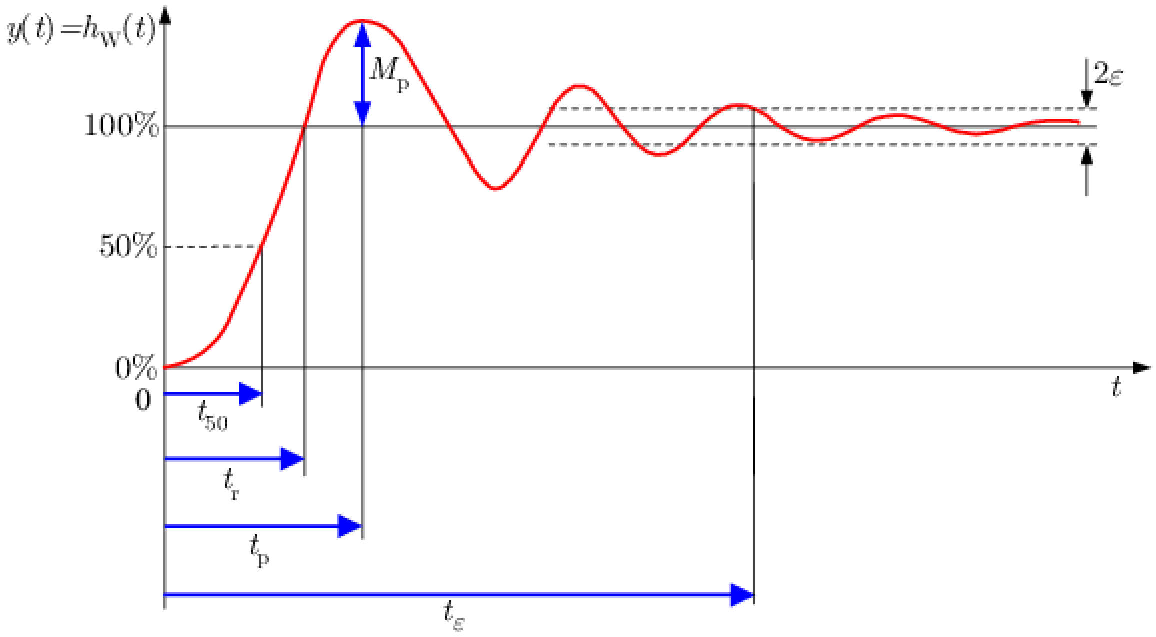

Fig.1.3: Under-damped response to unit step input

% Overshoot

It is the highest value of the response which can be calculated from unity.

Peak Time

It is defined as, how much time it will take to reach the 1st peak of the overshoot.

Rise Time

It is the time required for the response to reach from 10% to 90% for over-damped system or 0% to 100% for the under-damped system of its final value..

Delay Time

It is the time required for the response to reach half of its final value for the 1^{st} time.

1.4 PID Controller parameters

The primary work of a PID controller is to read a Set point and calculate the required output by calculating PID responses. The controller input is the error between the expected output and the final output. This difference is changed by the actuator of the controller to produce a signal to the plant, according to the following relationship

$$K(s) = K_P(1 + \frac{1}{\tau_i s} + \tau_d s) \tag{1.3}$$

1.4.1 P Controller

The proportional gain can be calculated as the ratio of the output response to the error signal. Generally speed of the control system response increases with the increase of proportional constant. One problem may also arise in proportional controller, if the gain is very large, then the process will start to oscillate. If it again increases, then the system will tend towards in-stability.

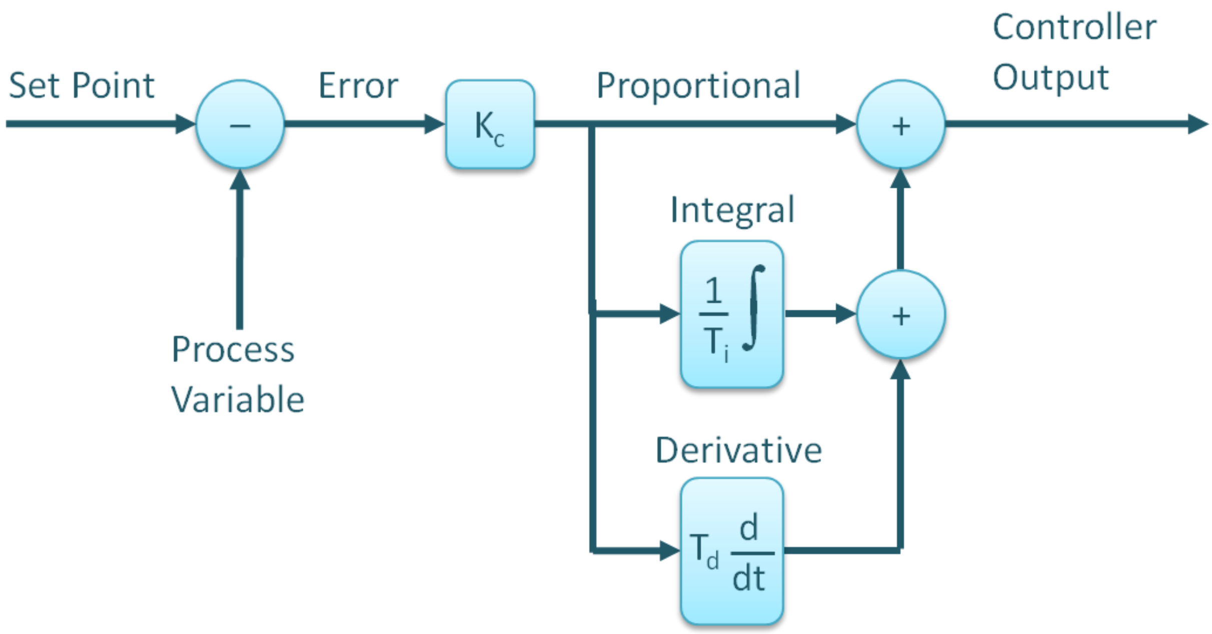

Fig.1.4: Basic diagram of the PID controller

In P controller only proportional constant need to be observed, the other two values integral constant and derivative constant is set to zero.

1.4.2 PI Controller

Integral component adds the error term over time. PI controller adds the small error term and increase the value of the integral component. It will increase the integral constant till error will become zero. So e_{ss} is zero in case of PI controller. That will also increase the time constant of the system so it will push the system towards instability.

1.4.3 PID Controller

The effect of each controller parameter K_P, K_i and K_d on a CLS is summarized in the table 1.1.

Table 1.1 Effect of controller parameters

Close Loop Response	Rise Time	Overshoot	Settling Time	Steady State Error
Kp	Decrement	Increment	Negligible Change	Decrement
Ki	Decrement	Increment	Increment	Zero
Kd	Small Change	Decrement	Decrement	Not affected

1.5 Motivation

The motivation for tuning of PID controller is mainly due to its wide application in process industries. It is widely used in programmable logic controllers, SCADA, remote terminal unit, etc. Because of high requirement of best tuning procedures which tune the plant in such a way that could provide optimized solution, many tuning methods have been developed so far in which some methods give better response for speed of the system and some show good response for stability. Thus, maximum methods are application oriented. FOPDT model is very popular because it is very easy to tune but for certain applications FOPDT model does not fulfill our requirements, so it is required to design such a system that attains the requirement of the applications. In the FOPDT model, it is not possible to generate peaks for monotonic system. So it is requred to design such a system that gives better stability and high speed of response. SOPDT model gives better response in both of the aspects, good stability and high speed of the response. In this research paper SOPDT model is proposed in which higher order system is reduced in a second order system.

1.6 Objectives

I. Development of a technique which satisfies all the requirements of a model. The requirements are peak overshoot is less than 15%, settling time should be as minimum as possible and speed of the response should be very high. Speed of response is inversely proportional to the time constant. Hence the time constant should be as minimum as possible.

II. Design of a second order model for both oscillatory and monotonic processes.

1.7 Thesis Organisation

The thesis is divided into 4 chapters.

Chapter 2: Literature Review

This chapter gives the idea of the tuning of PID controllers for FOPDT model. Many methods like Ziegler Nichol method and Cohen Coon method show hit and trail methods are being used for tuning in the initial days.

Chapter 3: Tuning of PID controller for the higher order system

This chapter is the heart of the total research work. It is divided into two methods for which we can tune the PID controller. In the first part of this chapter, tuning of the PID controller is based on the root locus method in which pole allocation strategy depends on whether the system is monotonic or oscillatory. In the second part of the chapter, tuning of the PID controller is based on Bode plot and Routh-Hurwitz method. We can find out the gain crossover frequency, phase crossover frequency and bandwidth frequency by using Bode plot. Routh criterion is used to get the value of k that to be critically stable and give finite gain crossover frequency and phase crossover frequency.

Chapter 4: Conclusion

The complete conclusion of the thesis work is described in this part of the paper. This chapter also describes the future research areas that need to work for further experimantation.

CHAPTER 2

LITERATURE REVIEW

Tuning of PID Controller by Gain-Phase Margin

Tuning of PID Controller by D partition rule

2 LITERATURE REVIEW

Since the last few decades, an extensive work has been done because of the growing popularity into process control industries. In very early nineties Ziegler-Nichol [2] gave tuning procedure for PID controller. Thereafter a large number of methods have been developed to tune PID controller for getting good responses. The main principles of some of the popular tuning methods have been discussed below.

- **Tuning of the PI controller based on gain margin and phase margin method** This method basically to attain specified G.M. and P.M. of the system [3-4]. This method is divided into two parts. In the first part, model poles are cancelled out by controller zeros, but poor result we expected because exact cancellation is not possible. In the second part, pole zero cancellation is not specified, so this method is more accurate than older one and got the excellent result.

- **Performances of gain margin and phase margins of popular tuning methods** The performance of PID controllers for dead-time to time constant ratio between 0.1 to1 has been discussed [5]. For load disturbance response different methods like Z-N method, Cohen coon method and ISE give a gain margin is approximately 1.5. These formulae are made for basically to cancel out a model pole to controller zero.

- **Tuning method of PID controllers for Desired Damping coefficient** This method proposes the tuning of first order plus dead time model [6]. One assumption has been made in this paper, to fix the derivative time and integral time, so that close loop transfer function degenerated. For given damping coefficient, the proportional gain can be approximated to linear function and understand the tuning method of PID controller that can be demonstrated the desired damping coefficient.

- **Tuning of PID controller by D partition rule** In this paper, tuning of FOPDT model has been proposed with the principle aim of increasing the degree of stability [7]. The presence of the delay time for the closed loop transfer function, it gives an infinite number of closed loop poles. For this system one cannot apply Routh-Hurwitz criterion. The D partition rule is developed to solve this problem. D partition boundaries analytically characterize so that a necessary condition of the maximum degree of the stability has been derived. After drawing the boundary and increasing the stability of the problem is changed into a set of optimization problem. After that converting results can be found out by using existing methods. The method is based on shifting left side of the imaginary axis by some distance so that few of the zeros of characteristic equation touches it and then using D partition concept and find out analytical expressions.

  The D partition theorem can be expressed as

$$\partial P = \partial P_0 \cup \partial P_w \cup \partial P_\infty$$

$$\partial P_0 = \{(k_P; k_I; k_D) \in \kappa : G_0(k_P; k_I; k_D) = \mathrm{f}(0; k_P; k_I; k_D) = \mathrm{k}_I = 0\}$$

$$\partial P_w = \{(k_P; k_I; k_D) \in \kappa : |\tau| = |k_D| \neq 0\}$$

$$\partial P_w = \{(k_P; k_I; k_D) \in \kappa : \mathrm{f}(\pm\, \mathrm{jw}; k_P, k_I, k_D) = 0\}$$

- **Tuning of PID controller using immune algorithm** This paper dedicated to tuning of PID controller using immune algorithm as well as G.M. and P.M. [8]. After deciding the G.M. and P.M. specifications, robust control is used to operate in the process. Using the exact value of immune algorithm the gain of the PID controller depending on the error between G.M. and P.M. The FNN based response is used to modify the result. As a result, G.M. and P.M. are written as

$$G_m = \frac{\pi\tau}{4kL}(1+\sqrt{1-\frac{4L}{\pi T_i}+\frac{4L}{\pi\tau}})$$

$$\Phi_m = \frac{1}{2}\pi - \frac{kk_pL}{\tau} + \frac{\pi}{4k_pk}(1-\frac{\tau}{T_i})$$

- **Simplified Disturbance rejection tuning method for PID controllers** The purpose of this paper is to show simplified disturbance rejection magnitude optimum (DRMO) tuning method [9]. These modifications shows fast and simple calculation for the PID controller and suitable for implementation. The disturbance rejection performance is the process for improving the low order system.

- **Performance Robustness Comparison of Two PID Tuning methods** In this paper, two methods are compared by their performance and robustness [10]. These methods are

(1) Desired Dynamic Equation method
(2) Gain and phase method

In the first method, two degrees of freedom are used in PID controller. There are two parameters, importing state observer parameter k and controller weight co-efficient l is used in this method. Final value of the controller can be written as

$$U = \frac{-t_0(\mathrm{x}-\mathrm{r}) - \mathrm{t}_1\, sx - \frac{k}{s+k}(\mathrm{s}^2\mathrm{x} - l\,\mathrm{U})}{l}$$

$$K_p = \frac{t_0 + t_1k}{l},\ K_i = \frac{kh_0}{l},\ K_d = \frac{h_1 + k}{l}$$

In the second method, G.M. and P.M. method is used to find out the values of the co-efficient of PID controller.

By comparison, we find that desired dynamic equation method has better performance indices than gain and phase method. In the desired dynamic margin method, peak overshoot is approximately zero, so the speed of the response is very high as compared to gain and phase method.

CHAPTER 3

Tuning of PID Controller for Higher Order System

Tuning of PID Controller by using root locus technique

Tuning of PID Controller by using Bode plot and Routh-Hurwitz

3 Tuning of PID Controller for Higher Order System

Tuning of PID Controller is conceptually easy, but tedious in practice. PID Controller is very popular in industries [11-12] because it is well known and result oriented [13-14]. A large number of studies have been done for the development of the tuning of the Controller. It is very common in the use of the FOPDT model because it is easy to tune and give better response than others. Many methods have been developed such as Ziegler-Nichols method [15], Cohen-Coon method, Inter model control (IMC) method, IAE-set point and IAE-load, ISE-set point and ISE-load, ITAE-set point and ITAE-load, which are basically very old and not much used in process industries. Now a day so many methods are developed which is application based.

3.1 Tuning of PID Controller using root locus technique

Many methods have been developed to find out PID controller parameters for SISO and multiple input multiple output (MIMO) systems [16-17]. In spite of the maximum of research works have been done in the literatures for auto tuning [18-21], many PID controllers are poorly tuned in practice. Most important reasons are that maximum of the tuning methods are derived for any specific applications [22-25] and therefore can be used only for the particular application.

Let us take a SOPDT system for getting the best response after tuning. In this method, first of all the higher order system is reduced in a second order system by using the model reduction technique. If we put s=jw, then the complex variable is divided into two parts after the angle condition is applied. In the FOPDT model for the monotonic system, we cannot generate peaks, but it is possible in case of the SOPDT modeling system. After getting the SOPDT, we need to design controllers which cancel out model poles. Closed loop poles have been selected according to the delay to dead time ratio, damping ratio and dead time model [26]. Satisfactory responses have been obtained by using this simple procedure than others.

FOPDT have only real poles not imaginary poles. Hence, they are not able to generate peaks for oscillatory processes. Thus, we are using second order plus dead time for PID tuning.

3.1.1 Higher Order reduction Method

The transfer function G(s) of a process is given in Eq. (3.1). The close loop controller is adopted as shown in Fig. 3.1.

Consider the SOPDT model with following structure:

$$G(s) = \frac{e^{-st_0}}{as^2 + bs + c} \tag{3.1}$$

Depending on the values of a, b, and c, the model can be characterized into real or complex poles. Hence it is easy to represent both non-oscillatory as well as oscillatory processes.

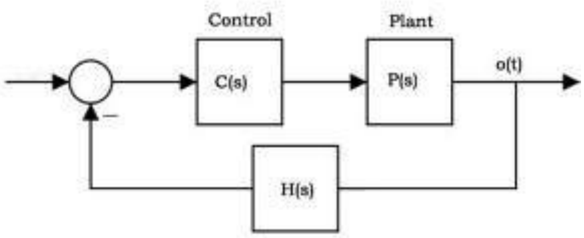

Fig. 3.1: Single loop controller feedback system

A PID controller can be written in the form of

$$K(s) = K_P + \frac{K_I}{s} + K_d s \tag{3.2}$$

The objective is to calculate K_P , K_I and K_D in such way that it improve the response of the system.

In Eq. (3.1) we can put $s = jw$, then divide into two parts that is real and imaginary part. We need four equations for finding out four unknowns. So by fitting the process gain G(s) at two nonzero frequency points it can be constructed into Eq. (3.2). Now we can pick the two different points $s = jw_c$ and $s = jw_b$ where $\angle G(jw_c) = -\pi$ and $\angle G(jw_b) = -(\pi/2)$ such that $G(jw_c) = |G(jw_c)|$ and $G(jw_b) = |G(jw_b)|$ It follows that

$$G(jw_c) = |G(jw_c)| \angle G(jw_c) \tag{3.3}$$

$$G(jw_b) = |G(jw_b)| \angle G(jw_b) \tag{3.4}$$

After dividing into real and imaginary parts, it is shown below

$$c - aw_c^2 = \frac{\cos(\mathrm{w}_c \mathrm{L})}{-|G(\mathrm{jw}_c)|} \tag{3.5}$$

$$bw_c = \frac{\sin(\mathrm{w}_c \mathrm{L})}{|G(\mathrm{jw}_c)|} \tag{3.6}$$

$$c - aw_b^2 = \frac{\sin(\mathrm{w}_b \mathrm{L})}{|G(\mathrm{jw}_b)|} \tag{3.7}$$

$$bw_b = \frac{\cos(\mathrm{w}_b \mathrm{L})}{|G(\mathrm{jw}_b)|} \tag{3.8}$$

After solving these equations we get the values of a, b and c that are given below:

$$a = \frac{1}{w_c^{\ 2} - w_b^{\ 2}} \left[\frac{\sin(w_b t_0)}{|G(jw_b)|} + \frac{\cos(w_c t_0)}{|G(jw_c)|} \right] \tag{3.9}$$

$$b = \frac{\sin(w_c t_0)}{w_c |G(jw_c)|} \tag{3.10}$$

$$c = \frac{1}{w_c^{\ 2} - w_b^{\ 2}} \left[w_c^{\ 2} \frac{\sin(w_b t_0)}{|G(jw_b)|} + w_b^{\ 2} \frac{\cos(w_c t_0)}{|G(jw_c)|} \right] \tag{3.11}$$

For getting the value of t_0 it is required to make an assumption

$$\frac{\sin(w_c t_0)}{\cos(w_b t_0)} - \frac{w_c |G(jw_c)|}{w_b |G(jw_b)|} = \Omega \tag{3.12}$$

Approximate sine and cosine function by the second order polynomial and then put this equation into Eq. (3.12), we get

$$-0.34({w_c}^2 - \Omega {w_b}^2){t_0}^2 + (1.7w_c + \Omega(0.11)w_b)t_0 - \Omega = 0 \tag{3.13}$$

After solving this equation, we can get the value of t_0 which is delayed function of the quadratic equation..

3.1.2 Tuning Method

For tuning of the controller, the range at which system is stable is first found out, by using Routh-Hurwitz criterion,

$$1 + G(s)H(s) = 0 \tag{3.14}$$

It is solved to give

$$k \le \frac{b}{t_0} \tag{3.15}$$

From here, we get the range of k for which system would be stable. The speed of response of a process is inversely proportional to its equivalent time constant τ_0. Equivalent time constant [27] can be found out as

$$\frac{1}{\tau} = \begin{cases} \dfrac{c}{\sqrt{b^2 - 2ac}} & b^2 - 4ac < 0 \\ \dfrac{b}{2a} & b^2 - 4ac \ge 0 \end{cases} \tag{3.16}$$

where a, b, c are model parameters that can be obtained from Eq. (3.9) to Eq. (3.11). The damping ratio can be defined as

$$\varepsilon_0 = \begin{cases} \dfrac{b}{2\sqrt{ac}} & b^2 - 4ac < 0 \\ 1 & b^2 - 4ac \geq 0 \end{cases} \tag{3.17}$$

The PID Controller can be rewrite in new form as

$$K(s) = k\frac{(\alpha s^2 + \beta s + \delta)}{s} \tag{3.18}$$

Where $\alpha = (K_D/k)$, $\beta = (K_P/k)$ and $\delta = (K_I/k)$.We choose the controller zeros which cancel out model poles i.e. $\alpha = a$, $\beta = b$ and $\delta = c$. Then resultant OLTF is

$$G(s)H(s) = \frac{ke^{-st_0}}{s} \tag{3.19}$$

In this method model pole have to be cancelled out by controller zero, but exact cancellation may not possible so approximate the zero to the nearest of model poles. For a process with a damping ratio less than one, un-cancelled dynamics may provide the heavy oscillations so it is not desirable to create one more oscillatory term in the system, but we can choose the real part of the close loop pole. For monotonic processes, un-cancelled dynamics do not create the process over oscillation so selection of close loop pile is advisable. Based on this theory, it is separated closed loop selection into four different parts.

Case1: $\varepsilon_0 > 0.7071$

In this case, both real and imaginary poles on the root locus can be chosen. For a pair of the required poles, $s = -\varepsilon_n w_n \pm w_n\sqrt{1-\varepsilon_n^2}$ To be lying on the root locus of the process, it follows

$$w_n = \frac{\cos^{-1}\varepsilon_n}{t_0\sqrt{1-\varepsilon_n^2}} \tag{3.20}$$

Now the value of k is assigned by magnitude condition

$$k = w_n e^{-w_n t_0 \varepsilon_n} \tag{3.21}$$

After phase condition are applied, then put damping ratio = 0.707

$$k = \frac{0.5}{t_0} \tag{3.22}$$

Case II: $\varepsilon_0 \le 0.7071$ and $0.15 \le \frac{t_0}{\tau} \le 1$

In this case, we can select two real poles of the closed loop poles on the root locus.

$$k = \frac{1}{\tau} e^{-\left(t_0/\tau\right)} \tag{3.23}$$

Case III: $\frac{t_0}{\tau} > 1$

In this case since delay to time constant is greater than 1 so the value of k is slightly greater than in case 1, which is given as

$$k = \frac{0.6}{t_0} \tag{3.24}$$

Case IV: $0.05 < \frac{t_0}{\tau} < 0.15$

In this case complex close loop pole presents so value of k is written as

$$k = \frac{0.4}{t_0} \tag{3.25}$$

New PID controller parameters are calculated as

$$\begin{bmatrix} K_P \\ K_I \\ K_D \end{bmatrix} = k \begin{bmatrix} b \\ c \\ a \end{bmatrix} \tag{3.26}$$

3.1.3 Result and Discussion

We can demonstrate some examples that will show that how to use this method and in Table 3.1 shows more simulation results.

Example 1: Let us consider the non-oscillatory system

$$G(s) = \frac{1}{(s+2)^2 (s+3)^2} e^{-0.4s}$$

Two points are $w_B = 0.7886$ and $w_c = 1.778$, frequency response at this point is $G(jw_B) = 0.02249$ and $G(jw_c) = 0.01148$

The model of the process is

$$\hat{G}(s) = \frac{1}{18.5s^2 + 47.3s + 35.89} e^{-0.7358s}$$

PID parameters are calculated as

$$K(s) = 32.144 + \frac{24.386}{s} + 12.573s$$

The response is shown in Fig. 3.2.

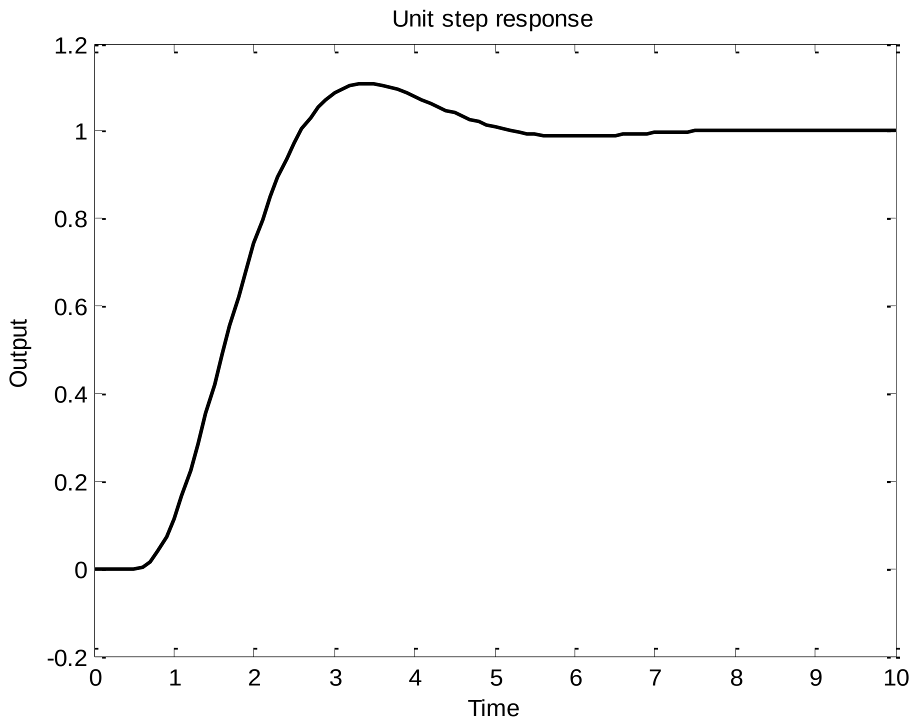

Fig. 3.2: Unit step response of the system
$G(s) = (1/(s+2)^2 (s+3)^2) e^{-0.4s}$

Percent overshoot is very less in this method that is desirable for any processes. Stability of the system is also very high because settling time of the model is very less which is shown in Table 3.1

Quantitative Analysis

Table 3.1 Response value for the step input

PARAMETERS	RESPONSE VALUES
% Overshoot	14%
Peak Time	3.2 sec
Rise Time	2.3sec
Peak Value	1.14
Settling Time	5sec

Example 2: Let us consider the oscillatory higher order system

$$G(s)=\frac{1}{(s^2+3s+2)(s+3)^2}e^{-0.1s}$$

Two points are $w_B=0.7521$ and $w_c=1.88$, frequency response at this point is $G(jw_B)=0.0391$ and $G(jw_c)=0.01365$

The model of the process is

$$\hat{G}(s)=\frac{1}{17.77s^2+31.39s+19.41}e^{-0.4984s}$$

PID parameters are calculated as

$$K(s)=31.497+\frac{19.479}{s}+17.832s$$

The response is shown in Fig. 3.3.

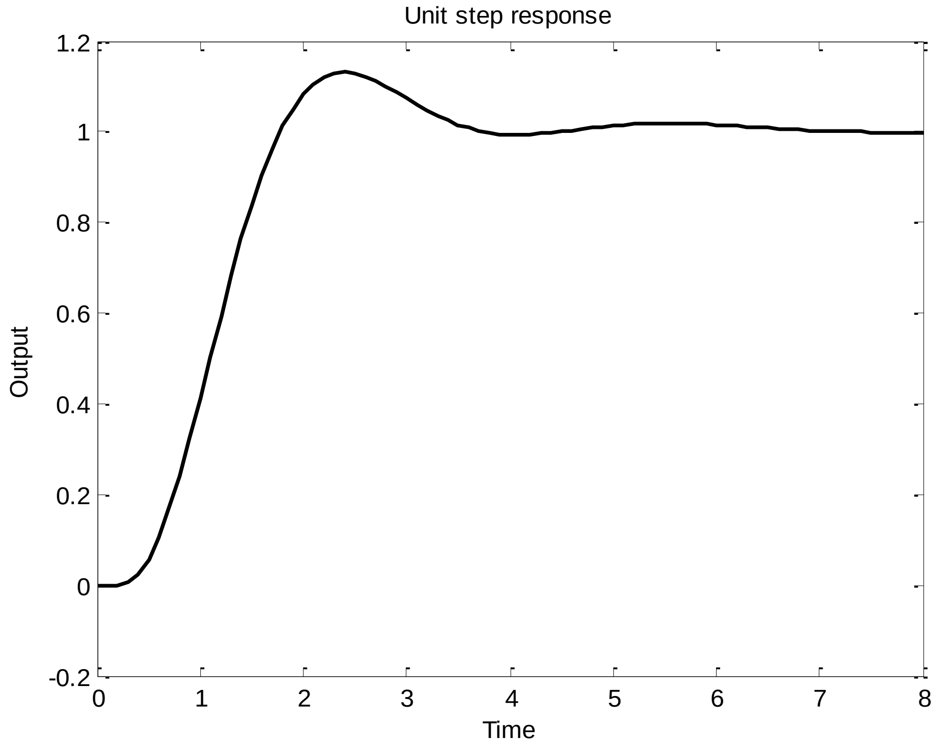

Fig. 3.3: Unit step response of the system

$$G(s) = (1/(s+3s+2)^2(s+3)^2)\,e^{-0.1s}$$

Percent overshoot is very less in this method that is desirable for any processes. Stability of the system is also very high because settling time of the model is very less which is shown in Table 3.2

Quantitative Analysis

Table 3.2 Response to the step input

PARAMETERS	RESPONSE VALUES
% Overshoot	16%
Peak Time	2.3 sec
Rise Time	1.7sec
Peak Value	1.16
Settling Time	4.1 sec

Example 3: Let us consider high oscillatory process

$$G(s)=\frac{1}{(s^2+2s+3)^3(s+3)}e^{-0.3s}$$

PID parameters are calculated as

$$K(s)=17.2+\frac{21.984}{s}+13.93s$$

The response of the system is shown in Fig. 3.4.

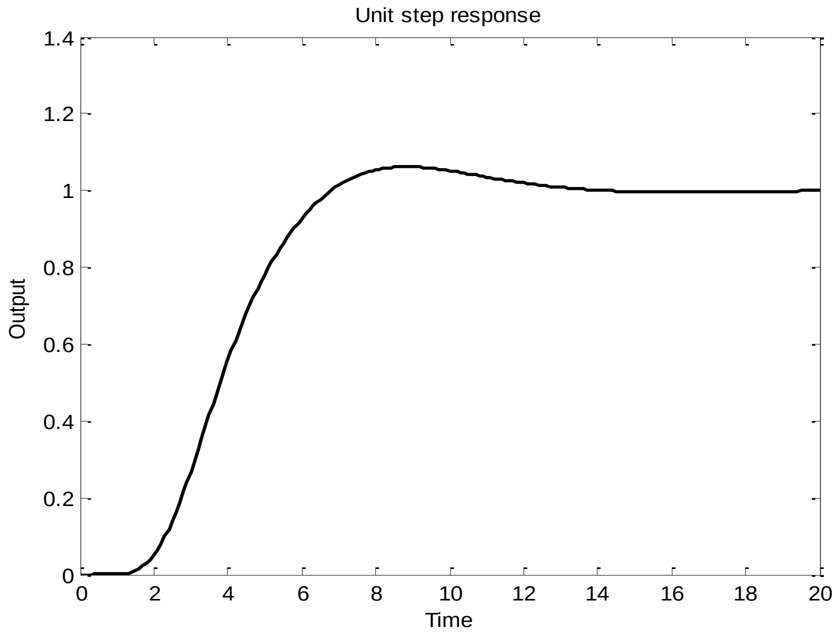

Fig. 3.4: Unit step response of the system
$G(s)=(1/(s^2+2s+3)^3(s+3))\,e^{-0.3s}$

In this seventh order system, percent overshoot is very less because in a higher order system, it is very difficult to get a response which is distortion less as well high speed of the response. Stability is also a major concern in the higher order system, but in this process, we get better response in both of the parameters which are shown in Table 3.3.

Quantitative Analysis

Table 3.3 Response to the step input

PARAMETERS	RESPONSE VALUES
% Overshoot	9%
Peak Time	7.8 sec
Rise Time	6.1 sec
Peak Value	1.09
Settling Time	10 sec

Example 4: Let us consider the oscillatory higher order system

$$G(s) = \frac{1}{(s^2+s+1)(s+2)} e^{-0.1s}$$

The model of the process is

$$\hat{G}(s) = \frac{1}{5.643s^2 + 4.953s + 4.495} e^{-0.8375s}$$

PID parameters are calculated as

$$K(s) = 1.5128 + \frac{1.5028}{s} + 1.7130s$$

PID parameters of Ho method

$$K(s) = 2.147 + \frac{1.484}{s} + 0.777s$$

PID parameters of Ziegler's method

$$K(s) = 3.2350 + \frac{1.9346}{s} + 13593s$$

The step response of the systems is shown in Fig. 3.5

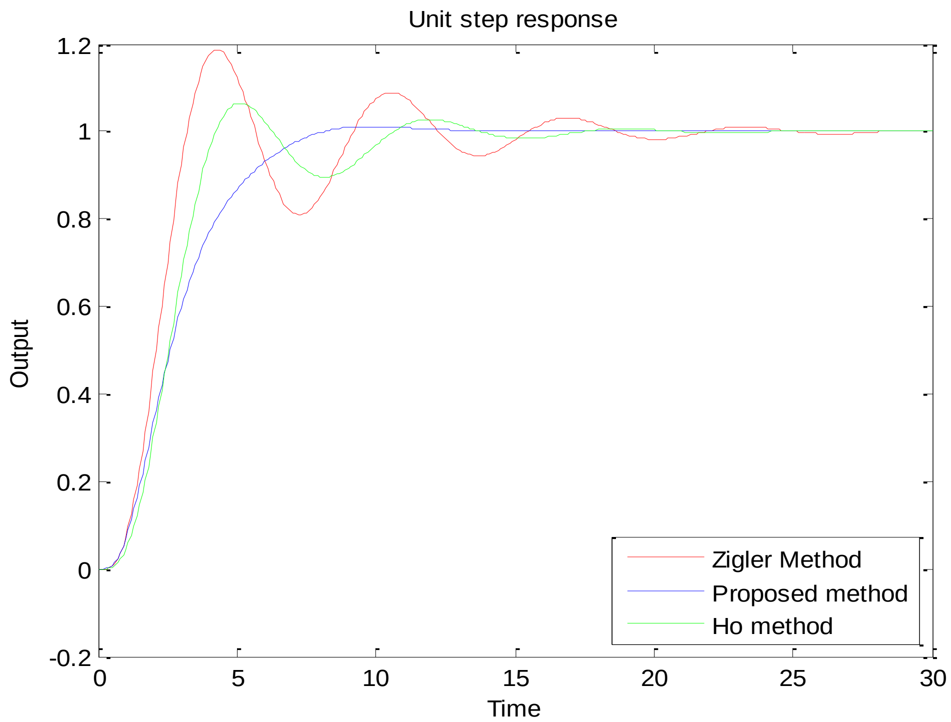

Fig. 3.5: Unit step response of the system
$G(s) = (1/(s^2 + s + 1)(s+2))\, e^{-0.1s}$

Quantitative Analysis

Table 3.4
Comparison between three methods

PARAMETERS	RESPONSE VALUES		
	Z-N method	Ho Method	Proposed
% Overshoot	20%	11.7%	3.0%
Peak Time	4.8sec	4.8sec	8.7sec
Rise Time	2.3sec	2.6sec	2.7sec
Peak Value	1.20	1.17	1.03
Settling Time	18.1sec	10.2sec	7.2sec

3.1.4 Summary

Tuning of PID controller by using the root locus method is for any dynamics; whether it is the high order or low order, high dead time or low dead time, the oscillatory or monotonic system. This method is also approximated on the basis of the Newton-Raphson method to bring the system very close to the exact value. The response of the system is highly improved in comparison to those older methods. The assigning of the pole is done by a root locus method to see whether pole lie on real part or imaginary part.

3.2 Tuning of PID Controller by Bode Plot Technique

PID controllers are popularly used in process control industries. Reasons for its wide implementation are simple structure and simple formulation. Tuning of FOPDT model is widely used for many applications unless they are not sufficient to fulfill specifications. In such applications we need to use SOPDT model for tuning of PID controller. Because of popularity in the process industries, lots of methods have been developed to find out the parameters of the PID controller such as a Z-N method, IAE, ITAE and IMC method. All the methods are surveyed and modified by Ho and Ho's method has been improved by Wang. In spite of enormous work done, but so many methods are poorly tuned. There are so many methods which are tuned well for a particular application, but fail for other applications. So, it is required to propose a model which is universally accepted and perform a task with high speed which is inversely proportional to the time constraint.

In this paper, tuning of PID controller is divided into two parts. Firstly, the higher order system is reduced in a second order system and secondly, PID controller is tuned. In the higher order reduction method, three frequencies namely, gain crossover frequency; phase crossover frequency and bandwidth frequency are required [27-29]. For a stable system, it is required to get a value that gives finite w_{gc} and w_{pc}. For finding the value of k, Routh-Hurwitz criterion is used. The value of k is multiplied to the numerator part of the process and then different frequencies are found out. The values of a, b, c and L can be calculated and they together form the SOPDT model.

3.2.1 Higher Order Reduction Method

The transfer function G(s) of a process is given in Eq. (3.28). The closed loop system is shown in Fig.3.6. A PID controller can be written as

$$K(s) = K_P + \frac{K_I}{s} + K_d s \qquad (3.27)$$

The tuning objective is to find out K_p, K_I and K_d in such way that it improves the system for all dynamics.

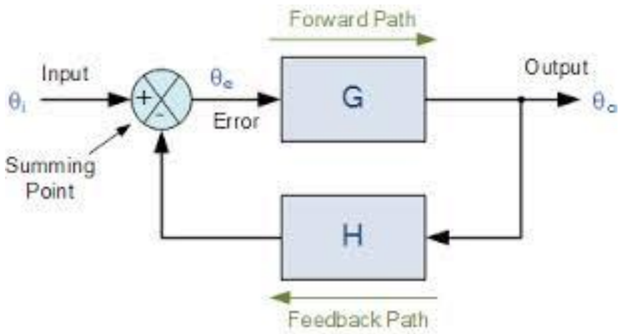

Fig. 3.6: Basic feedback system with controller

The second order model can be written as

$$G(s) = \frac{e^{-st_0}}{as^2 + bs + c} \qquad (3.28)$$

The reduction of higher order model in second order is done by the Bode plot method. Bode plot method is used in the sense that we can find out the values of w_{gc} and w_{pc}.

Suppose the higher order model is written as,

$$G_P(s) = \frac{k}{s^n + a_1 s^{n-1} + a_2 s^{n-2} + ...+ a_n} e^{-t_d s} \qquad (3.29)$$

Now numerator of the model is multiplied by unknown value k. The value of k is determined by Routh-Hurwitz criterion for which model would be critically stable. The value of k should be integer and just less than the value of the critically stable system.

For finding out Routh-Hurwitz stability, the characteristic equation is as follows

$$1 + G_P(s)\,H(s) = 0 \tag{3.30}$$

For unity feedback system,

$$H(s) = 1$$

In Eq. (3.28) there are four unknowns which are a, b, c and t_0. The Eq. (3.29) in frequency domain can be written as

$$G_P(jw) = \frac{k * e^{-t_d (jw)}}{(jw)^n + a_1 (jw)^{n-1} + a_2 (jw)^{n-2} + ... + a_n} \tag{3.31}$$

The magnitude part and phase part for second order model can be written as

$$A^2 + B^2 = \frac{1}{|G(jw)|^2} \tag{3.32}$$

$$\angle G(jw) = -\arctan(\frac{B}{A}) - t_0 w \tag{3.33}$$

where $A = c - aw^2$ and $B = bw$.

Eq. (3.32) is written as

$$A^2 + B^2 = \frac{1}{|G(jw)|^2} \tag{3.34}$$

or

$$\begin{pmatrix} w^4 & w^2 & w^0 \end{pmatrix} \begin{pmatrix} a^2 \\ b^2 - 2ac \\ c^2 \end{pmatrix} = \frac{1}{|G(jw)|^2} \tag{3.35}$$

In Eq. (3.35) a, b and c are not known. These variables can be found out by using the frequency response which is given in Eq. (3.29). Three frequencies, bandwidth frequency, w_{gc} and w_{pc} are to be calculated from Eq. (3.31).

These frequencies are used to find out the unknowns. If we find the magnitude part of the original system and phase part of the original system, then it is expected that the original model is same as the estimated model for any frequency.

Let us take,

$$\Theta = \begin{bmatrix} a^2 & b^2 - 2ac & c^2 \end{bmatrix}^T \tag{3.36}$$

$$\phi(\mathrm{w}) = \begin{bmatrix} w^4 & w^2 & w^0 \end{bmatrix} \tag{3.37}$$

The three frequencies are presented in a matrix Ω

which is

$$\Omega = \begin{bmatrix} w_b^4 & w_b^2 & w_b^0 \\ w_{gc}^4 & w_{gc}^2 & w_{gc}^0 \\ w_{pc}^4 & w_{pc}^2 & w_{pc}^0 \end{bmatrix} \tag{3.38}$$

and these gain parameters are presented in gain matrix N,

$$N = \begin{bmatrix} \dfrac{1}{|G(\mathrm{jw}_b)|^2} \\ \dfrac{1}{|G(\mathrm{jw}_{gc})|^2} \\ \dfrac{1}{|G(\mathrm{jw}_{pc})|^2} \end{bmatrix} \tag{3.39}$$

By using Eq. (3.36-3.39), it can be written as,

$$N = \Omega\Theta \tag{3.40}$$

Eq. (3.40) is written as

$$\Theta = \Omega^{-1} N \tag{3.41}$$

Let

$$\Theta = \begin{bmatrix} \alpha \\ \beta \\ \Upsilon \end{bmatrix} \tag{3.42}$$

The coefficient $a,\ b$ and c can be solved from Eq. (3.41)

$$a = \sqrt{\alpha},\ b = \sqrt{|\beta| + 2ac},\ \text{and}\ c = \sqrt{\Upsilon} \tag{3.43}$$

The delay of the projected model is calculated from the bandwidth frequency w_b as

$$t_{dr} = \frac{\theta}{w_b} \tag{3.44}$$

The modified T.F. is written as

$$G(\mathrm{s}) = \frac{e^{-st_0}}{As^2 + Bs + C} \tag{3.45}$$

where,

A = k*a; B = k*b; C = k*c

3.2.2 Tuning Method

Speed of response is inversely proportional to the equivalent time constant τ_0 of the process. For monotonic processes, speed of response is given by location of dominant poles (pole that is near to the origin) and for oscillatory processes, speed of the response is shown by non-imaginary part of complex poles.

$$\frac{1}{\tau} = \begin{cases} \dfrac{C}{\sqrt{B^2 - 2AC}} & B^2 - 4AC < 0 \\ \dfrac{B}{2A} & B^2 - 4AC \geq 0 \end{cases} \tag{3.46}$$

where A, B and C are model parameters. Damping ratio can be determined as

$$\varepsilon_0 = \begin{cases} \dfrac{B}{2\sqrt{AC}} & B^2 - 4AC < 0 \\ 1 & B^2 - 4AC \geq 0 \end{cases} \tag{3.47}$$

The PID Controller rewrites in new form as

$$K(s) = K\frac{(\alpha s^2 + \beta s + \delta)}{s} \tag{3.48}$$

Resultant OLTF is

$$G(s)H(s) = \frac{ke^{-st_0}}{s} \tag{3.49}$$

In this proposed method, controller poles are chosen such that it cancel the model poles. 100% cancellation is not possible because controller is a second order system, but processes can be of greater order. It can be divided into two parts. In the first part, it is possible that un-cancelled dynamics produces severe oscillations for oscillatory processes, so there is a possibility of creating additional oscillatory dynamics is very less. In the Second part, un-cancelled dynamics do not create severe oscillation for non-oscillatory or monotonic processes. Hence, some overshoot can be introduced by selecting complex close loop poles.

Hence, Process can be divided into two parts:

Case 1: $\varepsilon_0 \leq (1/\sqrt{2})$ and $0.20 \leq (L/\tau) \leq 0.95$

In this case as close loop poles are real poles, these lies on the negative real axis. In this system, it is easy to create complex conjugate poles that brought some oscillation in the system. So, the value of the K is calculated from the breakaway point in the root locus.

$$K = \frac{1}{\tau}e^{-(L/\tau)} \tag{3.50}$$

PID controller is modified as

$$\begin{bmatrix} K_P \\ K_I \\ K_D \end{bmatrix} = K \begin{bmatrix} 3*\mathrm{B} \\ C \\ A \end{bmatrix} \tag{3.51}$$

Case 2: $\varepsilon_0 > (1/\sqrt{2})$ and $0.95 \le (L/\tau) \le 2.00$

In this case, close loop poles are complex conjugate poles, which will lie on the imaginary axis.

The value of K is written as

$$K = \frac{2.5}{k*L} \tag{3.52}$$

PID controller is modified as

$$\begin{bmatrix} K_P \\ K_I \\ K_D \end{bmatrix} = K \begin{bmatrix} \mathrm{B} \\ C \\ 2*A \end{bmatrix} \tag{3.53}$$

Table 3.5: Simulation result for different plants

Plant	PID controller	Overshoot (Percent)	Settling Time (sec)	Peak Time (sec)	Delay Time (sec)
$G(\mathrm{s}) = \frac{1}{(\mathrm{s}+1)^2(\mathrm{s}+2)^2} e^{-0.5s}$	$2.465 + \frac{1.31}{s} + 1.42s$	8	11	7.7	3.4
$G(\mathrm{s}) = \frac{1}{(\mathrm{s}+1)^2(\mathrm{s}+4)} e^{-0.3s}$	$0.584 + \frac{1.121}{s} + 0.61s$	7.3	13	11	4
$G(\mathrm{s}) = \frac{1}{(\mathrm{s}^2+2\mathrm{s}+3)(\mathrm{s}+3)} e^{-0.3s}$	$3.72 + \frac{5.58}{s} + 1.65s$	2	5	3.2	2.7

3.2.3 Results and Discussion

The result is tabulated in Table 3.5 with different parameters as settling time, peak overshoot, peak time and delay time modified.

Example 1: Let us consider the non-oscillatory higher order process

$$G(\mathrm{s}) = \frac{1}{(\mathrm{s}+1)^2(\mathrm{s}+2)^2} e^{-0.5s}$$

The value of k which is calculated by Routh criterion is 10. Gain crossover frequency, Phase crossover frequency and bandwidth frequency is 1.0000, 1.0633 and 0.5574 respectively which is calculated from the Bode plot shown in Fig. 3.7.

The model of the process is

$$\hat{G}(\mathrm{s}) = \frac{1}{7.47s^2 + 4.3s + 6.83} e^{-2.06s}$$

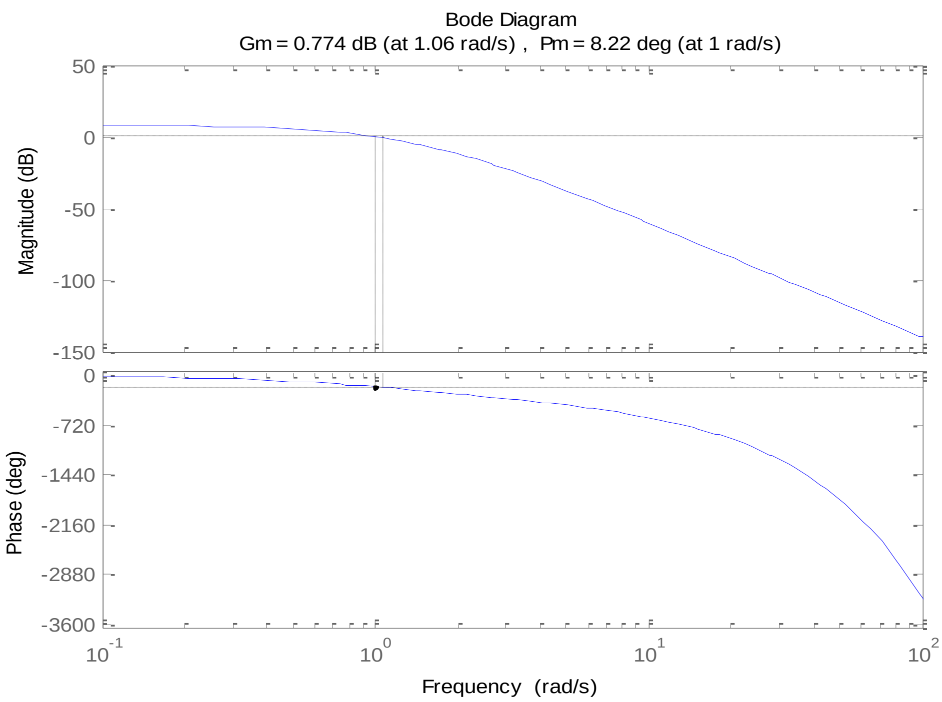

Fig 3.7: Bode plot of the process

$$G(\mathrm{s}) = \left(1/(\mathrm{s}+1)^2(\mathrm{s}+2)^2\right) e^{-0.5s}$$

PID parameters are calculated as

$$K(s) = 2.465 + \frac{1.31}{s} + 1.42s$$

Response is shown in Fig.3.8

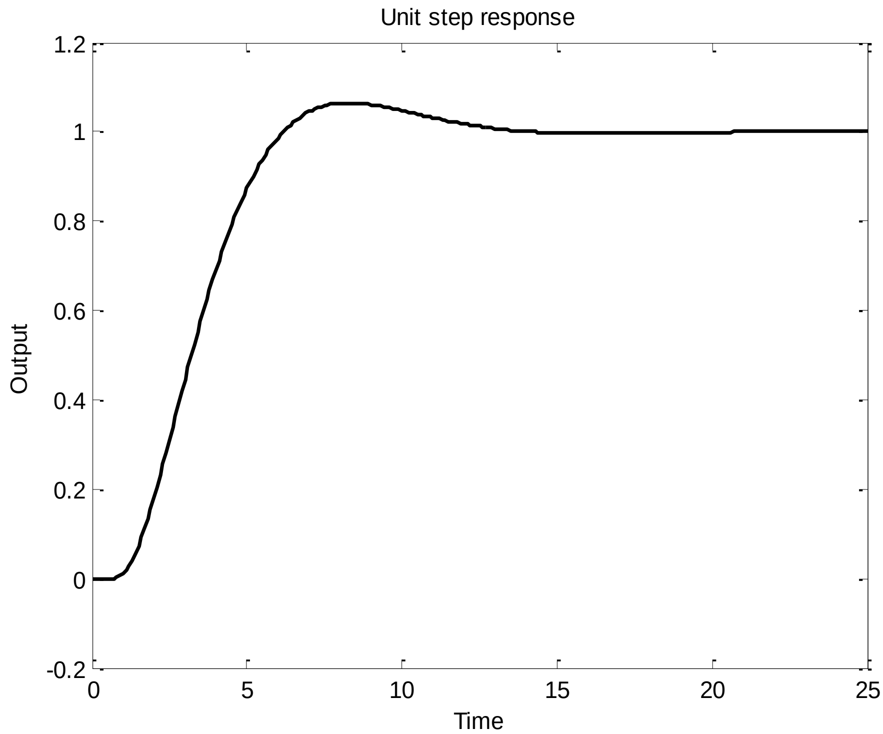

Fig. 3.8: Step response of the process

$$G(s) = (1/(s+1)^2(s+2)^2)\, e^{-0.5s}$$

Example 2: Let us consider the higher order non-oscillatory process

$$G(s) = \frac{1}{(s+1)^2(s+4)} e^{-0.3s}$$

The value of k which is calculated by Routh-criterion is 10. Gain crossover frequency, Phase crossover frequency and bandwidth frequency is 1.7057, 1.8530 and 0.6288 respectively which is calculated from the Bode plot which is shown in Fig. 3.8

The model of the process is

$$\hat{G}(s) = \frac{1}{1.596s^2 + 0.5054s + 2.907} e^{-1.78s}$$

PID parameters are calculate as

$$K(s) = 0.584 + \frac{1.121}{s} + 0.61s$$

The step response is shown in Fig. 3.10

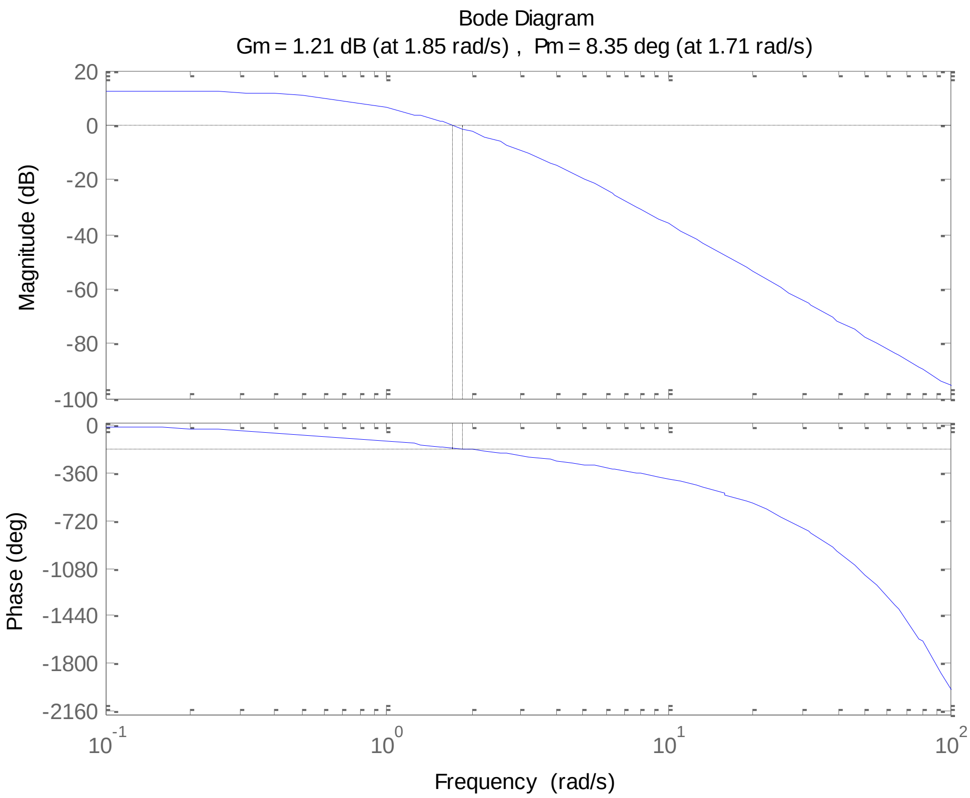

Fig. 3.9: Bode plot of the system

$$G(s) = (1/(s+1)^2(s+4))e^{-0.3s}$$

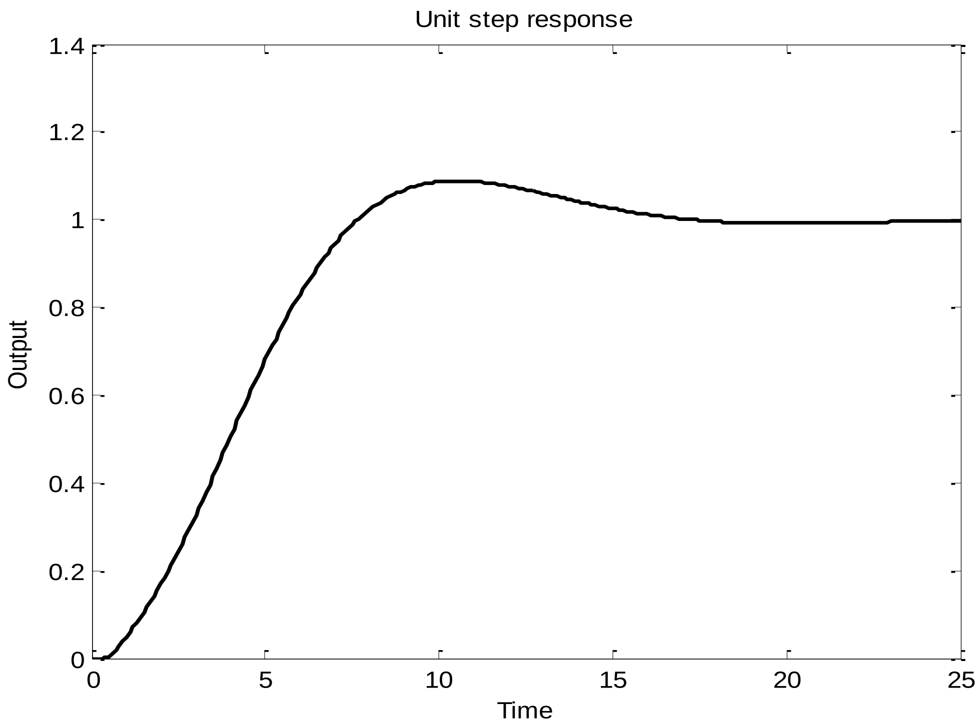

Fig. 3.10: Step response of the system
$G(s) = (1/(s+1)^2(s+4))\,e^{-0.3s}$

Example 3: Let us consider the oscillatory higher order process

$$G(s) = \frac{1}{(s^2+2s+3)(s+3)}e^{-0.3s}$$

The value of k which is calculated by Routh-criterion is 14. Gain crossover frequency, Phase crossover frequency and bandwidth frequency is 1.9291, 2.1051 and 1.8092 respectively which is calculated from the bode plot as shown in Fig. 3.11.

The model of the process is

$$\hat{G}(s) = \frac{1}{1.541s^2+8.844s+13.26}e^{-0.424s}$$

PID parameters are calculated as

$$K(s) = 3.72 + \frac{5.58}{s} + 1.65s$$

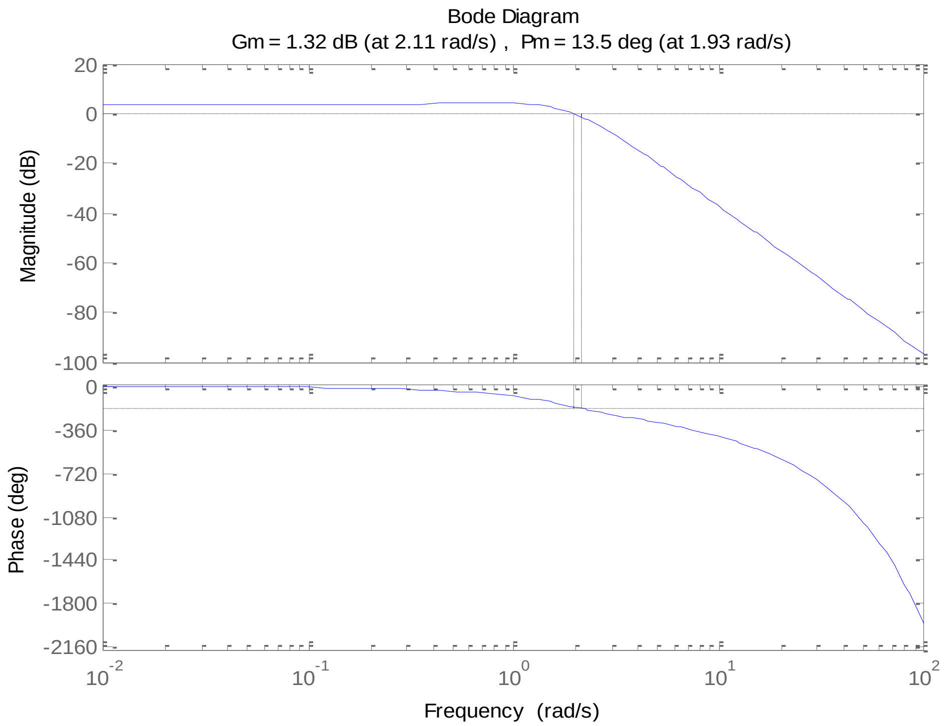

Fig. 3.11: Bode plot of the system $G(s) = (1/(s^2 + 2s + 3)(s + 3))e^{-0.3s}$

Response is shown in Fig. 3.12

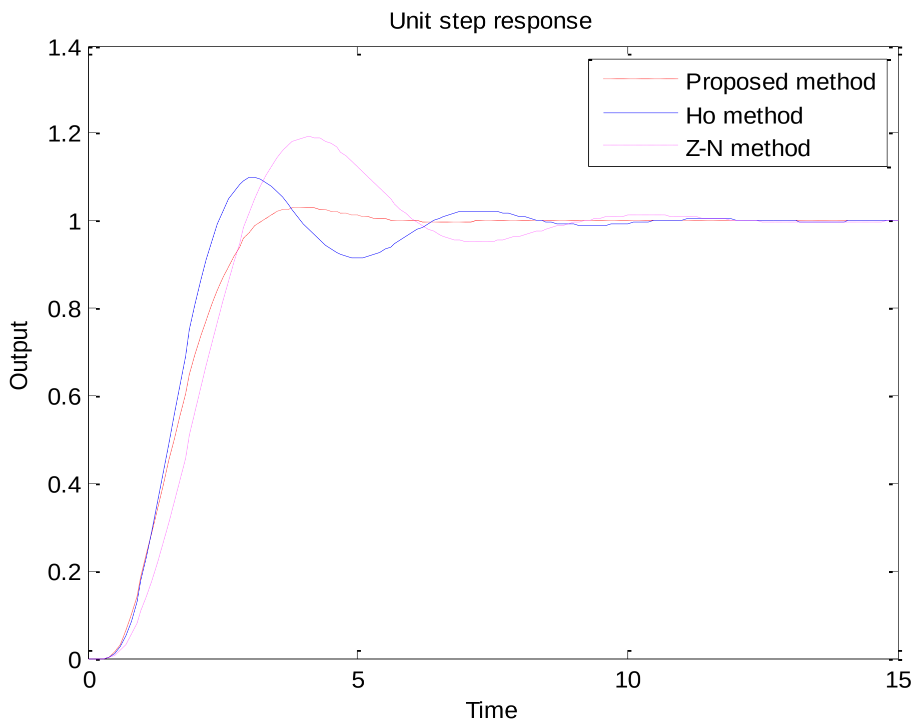

Fig. 3.12: Step response of the process $G(s) = (1/(s^2 + 2s + 3)(s + 3))e^{-0.3s}$

Quantitative Evaluation

A percent overshoot of the proposed method is very less as compared to the other two methods, which shows the effectiveness of the proposed method. Settling time of the system is also very less that shows the high speed of the system and system reach the zero error at very less time. Table 3.6 shows the different parameters of the result.

Table 3.6: Comparison of different parameters

Parameters	Response Value		
	Z-N Method	Ho Method	Proposed Method
% Overshoot	20	11.7	2.0
Peak Time(sec)	4.5	3.1	3.2
Rise Time(sec)	3.2	2.4	2.9
Peak Value	1.2	1.17	1.02
Settling Time(sec)	9.8	8.3	5.0
Delay Time(sec)	2.7	2.2	2.5

3.2.4 Summary

Tuning of PID controller by using Bode plot is very easy in practice. For reducing higher order model in second order, Bode plot have been used. In Bode plot method three frequencies have been found out (3db frequency, gain crossover frequency, phase crossover frequency), by using these three frequency models can be reduced in second order. The tuning procedure is basically on the basis of root locus technique in which pole allocation strategy has been taken as process pole is real or imaginary. Tuning process divided into two parts that is depending on damping ratio and delay time to time constant ratio.

CHAPTER 4

CONCLUSIONS

Conclusion

Future Work

4 CONCLUSIONS

This chapter concludes the research work and give the suggestion for future work.

4.1 Conclusion

In this research work, attention has been drawn towards the current trends of tuning of PID controllers for the higher order system. In modern process control industries, maximum attention is given to the development of such controllers which are most suitable for application based processes. The work started with the review of several methods of tuning of PID controllers for FOPDT. Most of the research work is done in FOPDT but the biggest problem of first FOPDT is that it is unable to generate peaks for monotonic systems. So it is required to generate such a system which can handle all such problems and that's why the SOPDT modeling is used to find out the controller parameters.

In the first part of the research work, the higher order system is reduced in a second order system by using angle condition in which two angle conditions are divided into four parts so that four variables can be solved. Tuning process is based on root locus technique in which, if model poles are monotonic (all poles lie on the negative real axis) then un-cancelled dynamics do not produce the oscillations. Hence some oscillatory dynamics are added to speed up the response and if the poles of the model are oscillatory then un-cancelled dynamics produces oscillations so it is not advisable to add oscillatory dynamics. Real closed loop poles can be chosen in such a case. This method provides a satisfactory response in both the aspects; the speed of the response or stability of the system.

In the second part of the research, model reduction method is based on Bode plot in which gain crossover frequency, phase crossover frequency and bandwidth frequency can be found out. Before using the Bode plot technique, we multiply numerator part of the process with k so that we can find out the value of k for which system is critically stable. The value of k is necessary because we need finite phase crossover frequency. After finding out the value of all the variables, it is required to multiply all the values with k so that it cancels out the influence of k. The tuning procedure in this process is somewhat similar to the previous one and is divided into two parts which is based on the root locus method.

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4.2 Suggestions for future Work

In process control industries, it is essential to design such systems that fulfill most of the requirements. Lots of work has been done to improve the response of FOPDT model, but in case of higher order plus dead time model, few research papers are published and a lot of work is to be done and improvement in tuning of PID controller has a lot of scope in process control industries. In this research paper, the higher order system is reduced in second order by two methods and then tuning procedure is applied. One can also directly tune the system without reducing it into second order form.

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DISSEMINATION OF THE RESEARCH WORK

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